

A METHOD FOR MEASURING THE EFFECTIVE THROUGHPUT TIME DELAY IN SIMULATED DISPLAYS INVOLVING MANUAL CONTROL

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SUMMARY

The advent and widespread use of the computer-generated image (CGI) device to simulate visual cues has had a mixed impact on the realism and fidelity of flight simulators. On the plus side, CGIs can provide greater flexibility in scene content than terrain boards and closed-circuit television-based visual systems can, and they have the potential for a greater field of view. However, on the minus side, CGIs introduce into the visual simulation relatively long time delays. In many state-of-the-art CGIs, this delay is as much as 200 ms, which is comparable to the inherent delay time of the pilot. Because most CGIs use multiloop processing and smoothing algorithms and are linked to a multiloop host computer, it is seldom possible to identify a unique throughput time delay, and it is therefore difficult to quantify the performance of the closed-loop pilot-simulator system relative to the "real world" task. This paper describes a method to address these issues using the STI-developed Critical Task Tester (CTT). Some empirical results from applying the method are presented, and a novel technique for improving the performance of CGIs is discussed.

BACKGROUND AND INTRODUCTION

Modern flight simulators usually employ a "host" digital computer in order to represent the mathematical model of the aircraft dynamics, the flight control system, the equations of motion, and the environmental disturbances. A "satellite" digital computer generates the dynamic external visual field which is output to one or more cathode-ray tube (CRT) displays. The combined process of generating and displaying the external visual field is usually referred to as a computer-generated image (CGI). The pilot "flies" the aircraft by monitoring the CGI, and his control outputs, ϕ , are inputs to the host computer. This closed-loop process is depicted in the block diagram shown in Fig. 1.

In order to conserve computer resources and minimize digital delays, both the host and the CGI computers usually employ multiloop architectures. In addition, the CGI computer uses smoothing algorithms in order to prevent the visual scene from "jumping" on the display. The data transfer between the host and CGI computers is almost always asynchronous.

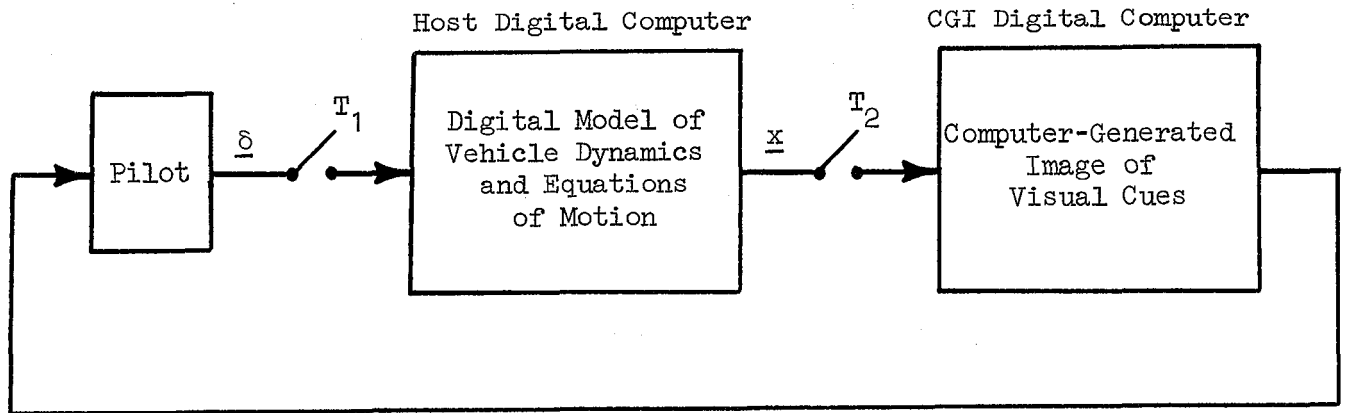


Figure 1. Functional Block Diagram of Architecture for Host and CGI Computers Used in Modern Flight Simulators

Because of the complex architecture used in the computers of modern flight simulators, it is very difficult to identify the effective time delay of the overall system, or, more importantly, to identify how the performance of the simulator compares to that of the real world. In many state-of-the-art CGIs, this delay is as much as 200 ms (Ref. 1), which is comparable to the inherent delay time of the pilot. For some flight tasks (e.g., up-and-away flight), this much delay is tolerable. For others (e.g., precision hover or landing), it is intolerable and completely unrealistic. When a pilot is unable to perform a task in a simulator, he often does not know exactly what is wrong; he knows only that he can perform the same task in the real world (Ref. 2). On the other hand, if the pilot can perform the task, he often complains that the workload is much higher than that in the real world. One explanation for both of these problems is that the pilot must generate lead in order to compensate for the lag in the CGI.

The primary purpose of this paper is to describe a method which can both measure the effective time delay of a modern flight simulator and quantify the performance of the closed-loop pilot-simulator system relative to the "real world." Since this method is independent of the hardware and software of the computers used in the simulator, it offers a rational means for evaluating hardware and/or software changes to any part of the flight simulator.

The remainder of this paper describes the proposed method and presents some empirical results of applying the method. A novel technique for improving the performance of visual simulators is also presented and discussed.

DESCRIPTION OF THE METHOD

The proposed method is based on human operator (HO) performance degradation in performing a manual control task. The particular manual control task is to stabilize an unstable controlled element using the critical tracking task (CTT, Refs. 3 and 4), as depicted in Fig. 2. The HO uses a manipulator, δ , to null the error, e , which is displayed on a CRT. The task is automatically paced in the sense that the unstable pole, λ , increases slowly with time, thus making the task progressively more difficult. At some point, the HO can no longer control the error, e , and the value of e exceeds a preset value. At this point, the task ends, and the corresponding final value of λ is defined to be the critical task score, λ_c .

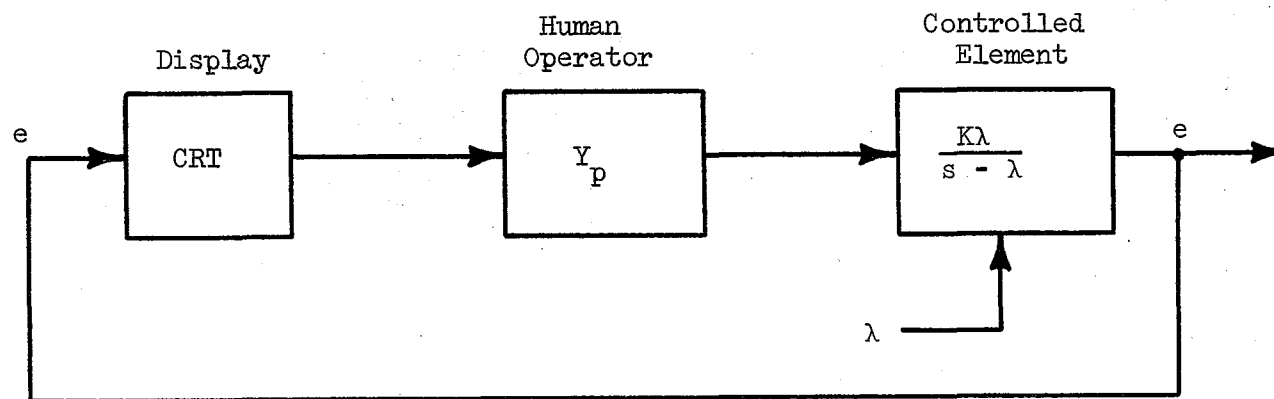
The CTT has been used in numerous experiments involving the human operator. Most of these experiments have examined the performance degradation of the HO due to exogenous effects such as alcohol, drugs, and prolonged bed rest (Refs. 5 through 8). It is also possible, however, to use the CTT in order to examine the performance degradation of the HO due to divided attention (Refs. 9 and 10) and other causes within the display (Refs. 11 and 12), the manipulator (Ref. 13), or the order of the unstable controlled element itself (Refs. 13 and 14). It is the causes of HO performance degradation between the operator's manipulator and a CGI display that forms the basis for the proposed method.

Consider now the modified CTT block diagram shown in Fig. 3. A CGI with sample update period, T_e , is now used to display the error signal, e . The control output of the HO, δ , is sampled at period T_δ . (T_e and T_δ were equal but not synchronized for the results described herein.) Figure 3 represents the essential features of a modern flight simulator that uses one or more digital computers to sample and process the pilot's output and a CGI to display the state of the vehicle to the pilot in terms of a simulated appearance of the external field of view. Figure 2 can be thought of as the "real-world" counterpart of Fig. 3, where the display is continuous, and there is no delay due to sampled data effects.

Because the variability in λ_c for a well-trained subject is sufficiently low (Refs. 3 and 15), the continuous (i.e., Fig. 2) and discrete (i.e., Fig. 3) versions of the CTT offer a unique means for comparing the effects of sampled data systems and CGI displays on the performance of the human operator.

SOME EMPIRICAL RESULTS

The results of an initial investigation of the effects of T_e and T_δ from the sampled, first-order CTT described in Fig. 3 are shown in Fig. 4. Note that the mean score, λ_c , is a linear function of the sample periods, T_e and T_δ . Also note that there is low variability in the data, as evidenced by the low values of the standard deviations. Using the zero time delay score as a reference point (i.e., $\lambda_c \approx 6.5$ rad/sec), the

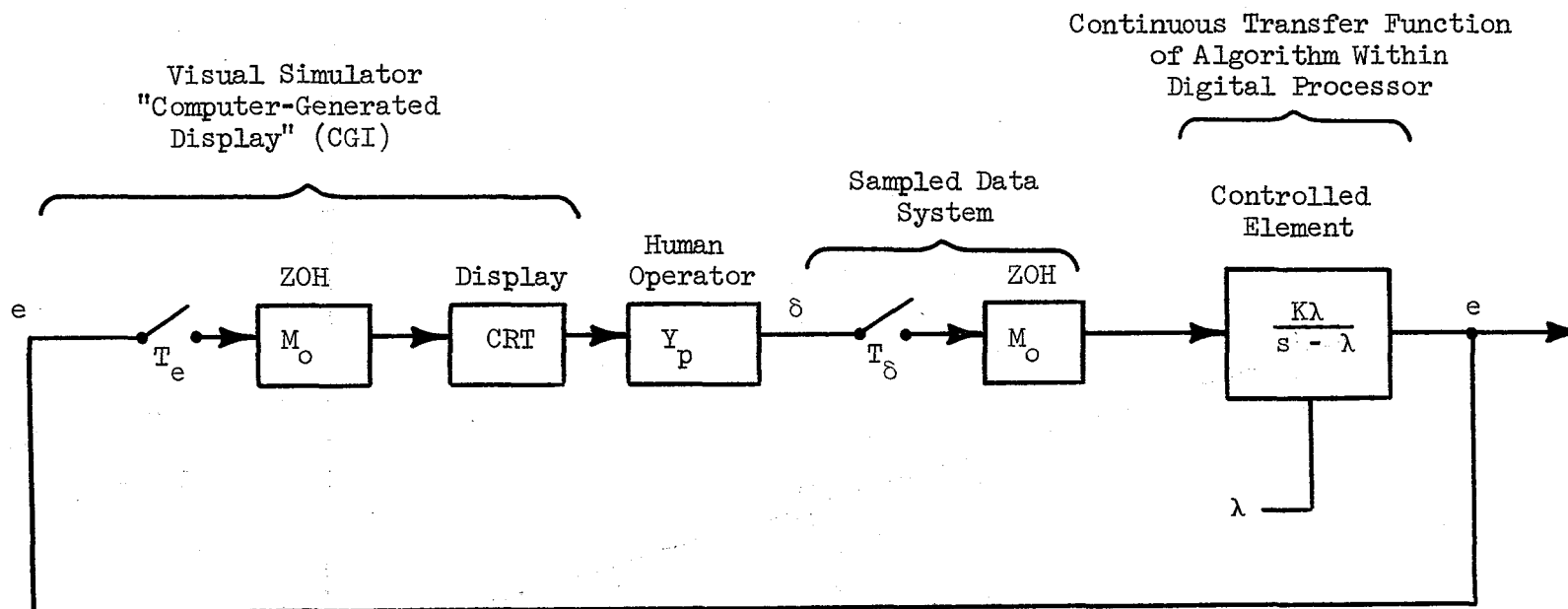


$$\lambda = \lambda_o + \dot{\lambda} dt$$

$$\dot{\lambda} = \begin{cases} 0.20 \text{ rad/sec/sec} & \text{for } |e| < e_c \\ 0.05 \text{ rad/sec/sec} & \text{for } |e| > e_c \end{cases} \quad \begin{array}{l} \text{one-way switch} \\ \downarrow \end{array}$$

Note: Task is automatically stopped when $|e| > e_s$

Figure 2. Functional Block Diagram of Critical Task Tester (CTT)



Note: The process of updating and holding a sample for one frame time, T , is modeled with a zero-order hold (ZOH):

$$M_O = (1 - e^{-Ts})/s$$

where T is the time delay associated with either T_e or T_δ

Figure 3. CTT with Computer-Generated Display and Sampled Data System

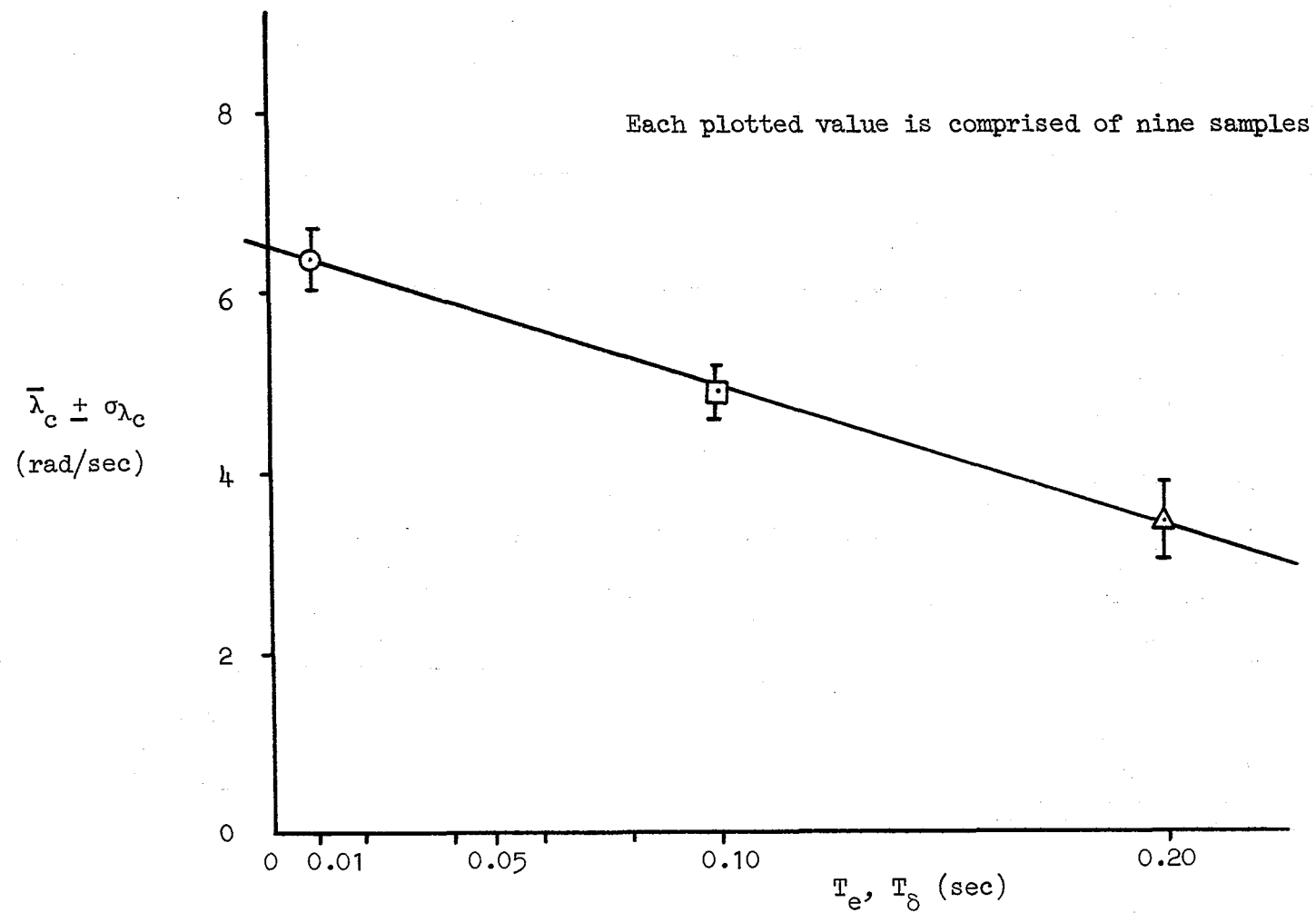


Figure 4. Effects of T_e, T_δ on λ_c

performance at 100 ms throughput delay is degraded by about 26 percent and, at 200 ms, by 49 percent! If we can extrapolate these results to other flight tasks, it is no wonder that pilots complain that they cannot perform real-world tasks in a flight simulator.

The discrete version of the first-order CTT in Fig. 3 thus offers a simple, convenient, and portable means for comparing the degradation in HO performance which accompanies throughput time delay and update rate between the pilot's manipulator and the CGI. It also meets the objectives stated at the beginning of this paper, i.e., to measure the effective time delay of a modern flight simulator and to quantify the performance of the closed-loop pilot-simulator system relative to the real world. The procedure for doing this in any given flight simulator is as follows:

1. Program the CTT algorithm in the host computer. Options for driving any one of the six axes of the CGI should be provided.
2. Establish a reference curve for λ_c versus the cycle time of the host computer. A separate curve must be established for each controller-display-operator combination.
3. Since the host computer will not be able to run at zero cycle time, each controller-display-operator combination must be extrapolated to the zero cycle time point. This point, λ_{co} , will be used as the "real world" reference point.
4. The effective throughput time delay of the total simulator, i.e., host computer and CGI, is calculated as follows:

$$T_{eff} = \frac{1}{\lambda_{ct}} - \frac{1}{\lambda_{co}}$$

where λ_{ct} is the value of λ_c at the normal operating point of the host computer. The above equation is based on the total throughput delay of the HO and digital computers being proportional to the inverse CTT score (Ref. 4). In general, the value of T_{eff} will not be the same as the "exact" throughput time delay. Hence the name "effective throughput time delay" is given.

Note that the procedure outlined above offers a rational means of evaluating the performance of a flight simulator. It also provides a method for evaluating changes to any component of the simulator. For example, the technique for improving the performance of a CGI that is discussed in the next section could be evaluated by this procedure.

A NOVEL TECHNIQUE FOR IMPROVING THE PERFORMANCE OF COMPUTER-GENERATED IMAGES

One way to compensate for the lag due to time delay in the combined host computer and CGI is to use lead in the signals being sent to the CGI. There are limitations in doing this, because the host computer cannot generate lead beyond the Nyquist frequency, and linear lead filters distort the amplitude response at the expense of obtaining the correct phase response. To overcome the first of these restrictions, the hybrid approach shown in Fig. 5 could be used.

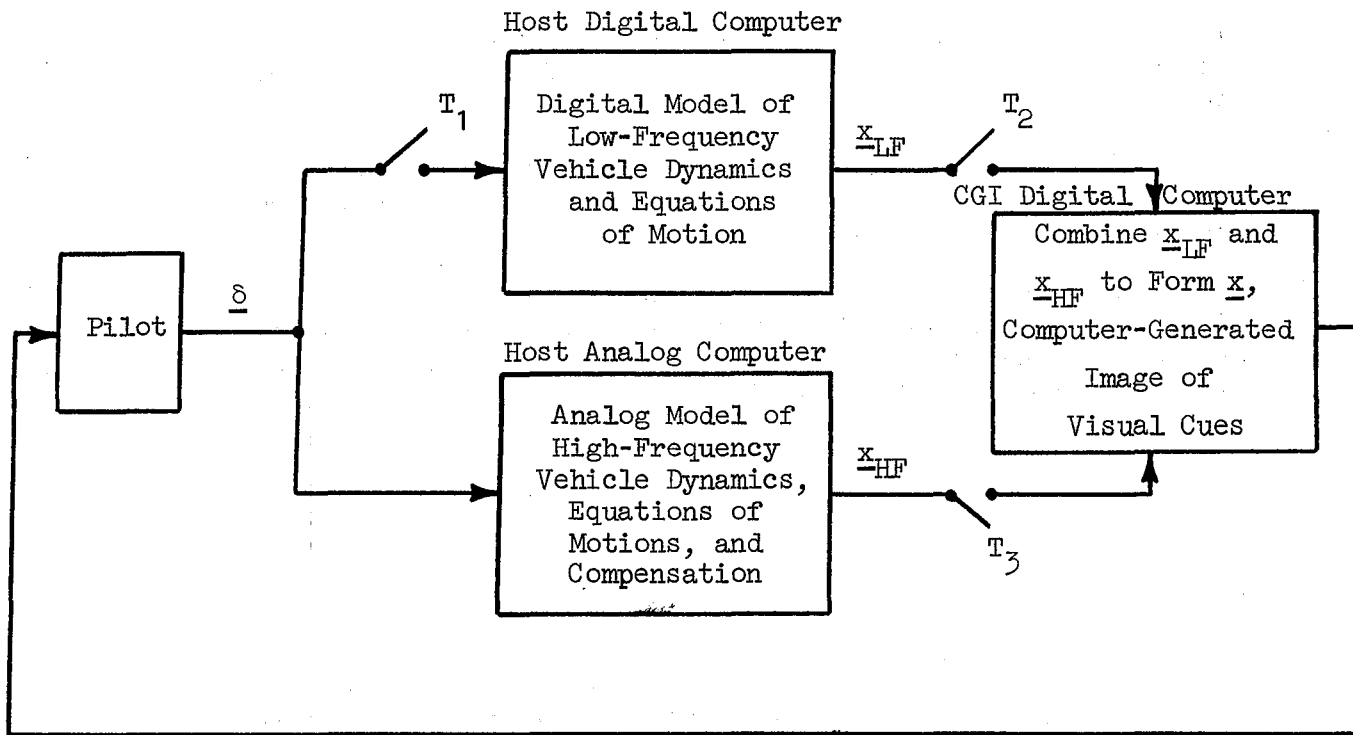
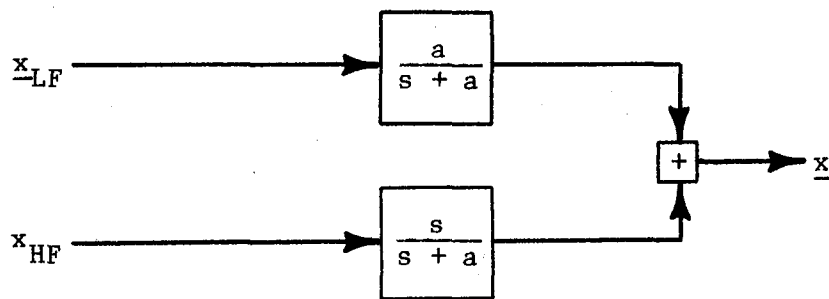


Figure 5. Functional Block Diagram of Advanced Hybrid Architecture
Proposed for Host and CGI Computers

Note that there are two "host" computers, one digital and one analog (hence the name "hybrid"). The host digital computer simulates the low-frequency vehicle dynamics (\underline{x}_{LF}), where "low frequency" means up to the Nyquist frequency, π/T_1 ; the host analog computer simulates the high-frequency vehicle dynamics (\underline{x}_{HF}), where "high frequency" means above π/T_1 ; and it compensates \underline{x}_{HF} to account for lags in the CGI digital computer. The CGI digital computer then combines \underline{x}_{LF} and \underline{x}_{HF} via "complimentary filtering" in order to form the final vehicle states, \underline{x} , which are displayed to the HO. A simple first-order complimentary filter is shown below,



where the break frequency, a , is chosen to be just below the Nyquist frequency, π/T_1 .

The compensation technique we propose to implement in the host analog computer was first reported in Ref. 16 and then later in Ref. 17. The technique, called the Split Path Nonlinear Filter or SPAN is shown in Fig. 6. The advantages of SPAN are that (1) it provides conditionally independent magnitude and phase angle specification (e.g., it can generate phase lead without amplitude distortion!) and (2) it is not dependent on input signal amplitude. On the other hand, the possible disadvantages of SPAN are that (1) the output will contain harmonic distortion which may need to be attenuated and (2) if the linear filter in the magnitude control path (F_m) contributes phase shift, it will be reflected in the output, hence the magnitude control path is conditionally independent.

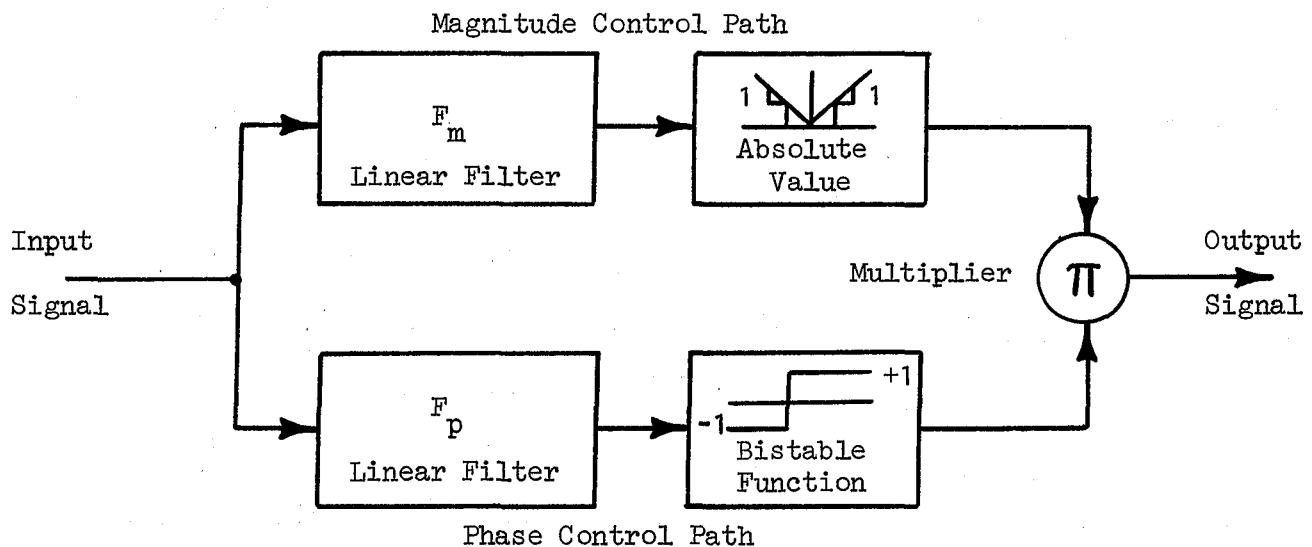


Figure 6. Flight Simulator Delay Compensation by Means of Split-Path Nonlinear Independent Magnitude and Phase Filters

The procedure outlined above needs to be tested under carefully controlled conditions. The CTT method described in this paper offers a unique way of quantitatively evaluating this novel technique for improving the performance of visual simulators.

REFERENCES

1. Paulk, Clyde H., Jr., David L. Astill, and Shawn T. Donley, Simulation and Evaluation of the SH-2F Helicopter in a Shipboard Environment Using the Interchangeable Cab System, NASA TM-84387, August 1983.
2. Woomer, Lt. C. (USN), and D. Carico, A Program for Increased Flight Fidelity in Helicopter Simulation, NATC TM 77-1 RW, April 27, 1977.
3. Jex, H. R., J. D. McDonnell, and A. V. Phatak, "A 'Critical' Tracking Task for Manual Control Research," IEEE Transactions on Human Factors in Electronics, Vol. HFE-7, No. 4, December 1966, pp. 138-145.
4. Jex, H. R., J. D. McDonnell, and A. V. Phatak, A "Critical" Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time. Part I: Theory and Experiments with a First-Order Divergent Controlled Element, NASA CR-616, November 1966.
5. Allen, R. Wade, Henry R. Jex, Duane T. McRuer, and Richard H. Klein, "Control Characteristics of Alcohol-Impaired Operators," AIAA Paper No. 74-1300, November 1974.
6. Allen, R. Wade, Stephen H. Schwartz, Anthony C. Stein, Raymond E. Magdaleno, and Jeffrey R. Hogue, Effects of Alcohol and Marihuana on Driver Control Behavior. Volume I: Laboratory Simulation Experiment, Systems Technology, Inc., Interim Technical Report No. 1066-1-I, April 1978.
7. Allen, R. W., and Henry R. Jex, "Visual-Motor Response in Crewmen During a Simulated 90-Day Space Mission as Measured by the Critical Task Battery," Seventh Annual NASA-University Conference on Manual Control, NASA SP-281, 1972.
8. Allen, R. Wade, and Henry R. Jex, Visual-Motor Response of Crewmen During a Simulated 90-Day Space Mission as Measured by the Critical Task Battery, NASA CR-2240, May 1973.
9. Jex, H. R., "Two Applications of the Critical Instability Task to Secondary Workload Research," IEEE Transactions on Man, Machines, and Systems, Vol. MMS-10, No. 4, December 1969, pp. 137-140.

10. Allen, R. W., W. F. Clement, and H. R. Jex, Research on Display Scanning, Sampling, and Reconstruction Using Separate Main and Secondary Tracking Tasks, NASA CR-1569, July 1970.
11. Jex, Henry R., R. Wade Allen, and Raymond E. Magdaleno, Display Format Effects on Precision Tracking Performance, Describing Functions, and Remnant, AMRL-TR-71-63, August 1971.
12. Jex, H. R., R. W. Allen, and R. E. Magdaleno, "Vibration Effects on Manual Control Performance," Eighth Annual NASA-University Conference on Manual Control--University of Michigan, AFFDL-TR-72-92, May 1972.
13. McDonnell, J. D., and H. R. Jex, A "Critical" Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time. Part II. Experimental Effects of System Input Spectra, Control Stick Stiffness, and Controlled Element Order, NASA CR-674, January 1967.
14. Jex, H. R., and R. W. Allen, "Research on a New Human Dynamic Response Test Battery. Part I: Test Development and Validation. Part II: Psychophysiological Correlates," Sixth Annual Conference on Manual Control, AFIT/AFFDL Report, Conference Paper G-5, April 1970.
15. Jex, H. R., W. F. Jewell, and R. W. Allen, "Development of the Dual-Axis and Cross-Coupled Critical Tasks," Eighth Annual NASA-University Conference on Manual Control--University of Michigan, AFFDL-TR-72-92, May 1972, pp. 529-552.
16. Levinson, Emanuel, "Gain-Phase Relations of Nonlinear Circuits," IRE National Convention Record, Part 4, 1958, pp. 141-152.
17. Foster, W. C., D. L. Gieseking, and W. K. Waymeyer, "A Nonlinear Filter for Independent Gain and Phase (With Applications)," Transactions of the ASME, Journal of Basic Engineering, June 1966, pp. 457-462.